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A MEASUREMENT OF LONG-TERM TILT IN COLORADO AND WYOMING.

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- Borehole tiltmeters are conceptually attractive for monitoring long-period crustal deformation and the spatial variations of tidal tilt response due to crustal inhomogeneities. A major part of this research has been devoted to the development and testing of comparatively inexpensive instruments suitable for deployment in standard 6-inch diameter cased holes drilled to industrial tolerance(vertical to within 5 degrees), and also sufficiently sensitive and stable for earth tide studies. The present system is composed of a stainless

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Abstract -- Block 20 continued

steel capsule, six feet in length, pressed by flat springs against a stainless steel casing section at the bottom of a hole cased with standard steel pipe. The capsule contains two tilt sensors on a leveling platform. Each sensor is composed of a pendulum whose position is sensed by means of a capacitance bridge. Most of the electronics are installed with the sensor at depth to reduce the temperature sensitivity of the system. Field tests have shown that surfician effects are large at a depth of 20 feet, that these effects are negligible at 100 feet, and that no further improvement is apparent at 200 feet. Measurement of the azimuthal orientation is made with a series of alignment rods. As it is difficult to extend this method to instruments deeper than 100 feet, that depth has been selected for standard installation. Data acquisition systems include both those using dedicated telephone lines and those using periodic dial-up with interim storage of the data at the field site. The software developed includes a set of modular analysis routines with advanced graphics capability. Future work is oriented toward an advanced test installation in Eastern Colorado and operational deployment in the Yellowstone Park region of Wyoming.

SUMMARY OF OBJECTIVES

1. To conduct field and laboratory measurements of long term crustal motions at periods longer than four minutes.

2. To install two borehole instrument systems about 1 kilometer apart near Boulder, to investigate their coherence and evaluate the influence of local effects.

3. To develop and deploy an array of instruments in Wyoming, Montana, or Colorado.

INTRODUCTION

This report describes the first two years of development work on a borehole tiltmeter by the University of Colorado under contract F-19628-78-C-0065 with the Air Force Geophysics Laboratory, Air Force Systems Command.

The objectives of the three year program are two-fold:

(1) To design an inexpensive borehole tiltmeter which can be installed below the superficial layers of the earth affected by meteorological influences (mainly rainfall).

(2) To install a number of these instruments to measure long term crustal tilts and to determine the feasibility of making long term tilt measurements with instruments of this type.

As part of the program to measure long term crustal tilts, we will measure the earth tides with moderate accuracy (1% in M2 using 3 months of data). These measurements can serve both as a calibration and test of the instrument and as an evaluation of the possibility of using spatial variations in the tidal tilt response as a probe of elastic inhomogeneities in the earth.

We were encouraged to undertake this investigation by the excellent performance and potential of the borehole tiltmeter designed by A. Graf (Zschau, Flach, et al., 1975) and manufactured by the Askania Company (later Bodenseewerk). This instrument is too expensive to use in the quantity necessary to attack the geophysical problems in which we are interested, however.

CONCEPTS AND OVERALL DESIGN

The desire for an inexpensive and relatively [e installation led to several constraints on the borehole to be used: it should not be deeper than necessary and no ususual constraints in terms of straightness or verticality should be required. Discussions with a well-drilling company revealed that there is a significant increase in the complexity of the drilling equipment required for holes larger than about 6 inches in diameter, and we therefore decided to start with 6 inch diameter holes. Our experience to date seems to confirm our initial estimates that holes about 100 feet deep are satisfactory, and that the only difficulty in going deeper is in determining the orientation of the instruments when they are at the bottom of the hole. We also planned to exclude ground water from the hole so that it would not be necessary to stabilize the tiltmeter against varying hydrostatic forces as the water level in the hole changed.

A study of tilt-strain coupling in boreholes (Harrison, 1976) shows that there is no cavity effect if the side of the hole is used as a reference for the tiltmeter. There is only a small cavity correction if, as in the Askania tiltmeter, the center of the bottom of the hole is used as one reference point.

The tiltmeter capsule is about 6 feet long and is made of stainless steel. The capsule rests in an 8 foot long section of stainless steel pipe at the bottom of the hole. The capsule is pressed against the sides of the outer stainless steel pipe by two flat springs. Contact is made at four raised points on the capsule -- two near its top and two near its base. The bottom of the capsule rests on a stainless steel ball loosely held in a small clamp. This ball rests on a plate of stainless steel welded to the end of the outer pipe, and it supports the weight of the capsule. We have changed this bottom support slightly as discussed below. The basic principle is, however, the same.

In order to avoid tight tolerances on the verticality of the borehole, the tilt sensor is mounted on a levelling platform designed to be able to tilt the instrument by up to 5 degrees in two perpendicular directions. This places limits on the size of the sensor, but within these limits, a variety of different sensing techniques may be used.

In parallel with our work on the boreholes and the tilt sensors, we also developed hardware and software for data acquisition and processing. To keep the cost of each site to a minimum, our datalogger uses a central computer linked to each site via dedicated telephone lines. The hardware required at each site is then quite small, since all of the timing and data storage is done by the central machine. In addition to data acquisition, the central machine is also used for routine data analysis. The remote datalogger system can also transmit commands to the tilt sensors. This could be used to re-zero them, for example. This capability is not used at present.

MECHANICAL DESIGN

A 6-inch diameter borehole is drilled to the required depth and several buckets of cement are poured down the hole. The casing is then lowered down the hole. The casing is composed of one 8-foot long stainless steel bottom section for the capsule and as many 21-foot long carbon steel sections as are needed to reach to the required depth. The casing is welded into one continuous pipe as it is lowered down the hole.

The bottom section is 4.5 inches in outside diameter, has walls 0.25 inches thick and is closed at the lower end with a bottom plate welded on in the shop. The top of this section has a transition section to the standard carbon steel pipe which is 5 5/16 inch diameter with .125 inch wall. The grout at the bottom ensures that at least the instrument compartment is securely cemented to the rock.

Additional grout is poured in from the surface around the outside of the casing.

The instrument capsule (see fig. 1) is a 6-foot length of stainless steel tubing closed at the bottom and having a pair of contact points and a flat spring welded on near its top and a second pair with a second flat spring near its bottom. In the first version the weight of the capsule was supported by a caged steel ball mounted on the base of the capsule; in the present version the flat base of the capsule rests on a hemispherical knob on the base of the instrument compartment. In both cases the idea is to allow the bottom to move easily from side to side so that the capsule position is determined by the contact points positioned against the sides of the instrument compartment. The top of the capsule is sealed with a cap attached by screws that compresses a trapped O-ring. The cap has a water-tight opening for the electrical cable feed-through, hooks for attaching the one-quarter inch diameter lifting cable, and a post for attaching the orientation rod (see below).

The levelling platform (see fig. 2) consists of a baseplate, one fixed and two moveable levelling screws driven by motors through reduction gear boxes, and a mounting plate. In the first version the levelling screws had 300 threads per inch. These screws were too easily stripped, and we now use 90 threads per inch. The baseplate is attached to the capsule by three set screws with conical tips threaded through the side of the capsule and entering conical holes in the side of the baseplate. (The integrity of the capsule is maintained by sealing these screw holes with silicon rubber applied to the outside of the capsule after the sensor is inserted.) We have experienced no great difficulty in zeroing instruments to within a few microradians using this system.

It is necessary to determine the azimuth of the capsule. Techniques using the earth's magnetic field cannot be used since the casing is magnetic. We tried to sight on the top of the capsule to determine its orientation, but this technique is not adequate in general and is usually impossible for holes deeper than 50 feet since the capsule is often not visible from the surface. After several different schemes were tried, we developed a system involving a series of light rods. The first is attached to a post at the top of the capsule just before it is lowered into the casing. This post is aligned with the axes of the tiltmeters. (It is exactly parallel to the sensitive axis of one sensor and hence is perpendicular to the sensitive axis of the other.) As the capsule is lowered, additional sections of rod are added. Each section is notched so that it can only be attached in one orientation. Thus when the capsule is at the bottom, the orientation of the top notch is the same as the orientation of the tiltmeter. After the orientation of the top notch is determined (using a transit or a compass), the entire series of rods is removed from the capsule by simply lifting gently (all of the intermediate joints are held fast by screws. The bottom rod is joined to the capsule using a spring loaded ball in an indent and therefore is easily removed.) This technique has been used to determine the orientation of instruments at the bottom of 100-foot-deep holes, but there is certainly a limit to the depth at which it can be used satisfactorily, and this is presently the limiting factor determining the depth at which our instruments can be used. If it proves necessary to operate instruments at depths much greater than 100 feet, it will probably be necessary to use some other method of determining the orientation of the instrument. One possibility would be to use a gyrocompass in the tiltmeter capsule.

The capsule and levelling system can be used with any sensor small enough to fit on the levelling platform and with sufficient clearance for alignment. We have used two single axis simple pendula of 5 cm length manufactured by INSTECH (Larry Burris) of Austin, Texas in almost all of our capsules to date. These sensors function extremely well at sensitivities somewhat less than that in which we are interested. Because of their small mechanical sensitivity, the gain of the electronics must be made unreasonably high to be able to resolve the earth tides, and the resultant electronic noise degrades the earth tide measurements to an unacceptable degree. We have improved the electronics considerably during the last six months, but it is not clear that we have succeeded in reducing the noise of the amplifiers to the point where tidal tilts could be accurately measured. It is possible that the very low mechanical sensitivity of the 5 cm pendulum will preclude its use at tidal sensitivity.

To improve the overall sensitivity we have acquired two additional sensors from INSTECH with higher mechanical sensitivity. One of these uses a horizontal pendulum with a one second free period (an effective length of 25 cm) and the other uses a straight-line level (LaCoste, 1973) with a period of three seconds (an effective length of 225 cm). We have begun to use these instruments, but we have no results as yet.

ELECTRONICS

The design of the electronics package has evolved considerably during the course of the work, but the basic principle remains the same. The sensor is basically a capacitance bridge. Two fixed plates on either side of the moving mass are driven out of phase by a sine wave generator oscillating near 10kHz. The signal received by the center (moving) plate is amplified and measured using a phase sensitive detector. The output of this system is a d.c. voltage proportional to the deviation of the mass from the electrical center of the system provided the deviation is small.

Although the system is simple in principle, it is quite difficult to make a very stable readout in practice. The capacitance between the center plate and either end plate is a few picofarads, and it is very easy for stray capactiances to be of the same order of magnitude. Fluctuations in these stray capacitances induce changing currents that look just like tilts.

A second major difficulty comes from the phase instability of the driver amplifiers for the outer plates. A readout based on the phase of the voltage at the center plate assumes that the two outer plates are driven with precisely the same amplitude and precisely opposite phase so that the electrical zero of the system occurs at the mechanical center of the system. Although small deviations from this ideal situation are tolerable if they are stable in time, any change in the relationship between the outer plate voltages will produce a "tilt" signal. The stability of this relationship is thus of paramount importance. Our first system defined the relationship between the voltages on the two outer plates by means of a high-quality operational amplifier operating in a conventional inverting configuration with a gain of -1. This method of generating the drive voltage for the outer plates assumes that the ratio of the two resistors in the inverter is at least as stable as the tiltmeter assembly. Our present system uses a center-tapped transformer to produce the two out-of-phase voltages. Such a system depends on the stability of the secondary of the transformer. In both cases, we must depend on the stability of various electrical components, in spite of the fact that these components are neither built nor tested for this parameter by the manufacturer. It is not clear that one system is much better than the other. The chief advantage of the transformer is that it is small and takes no external power source, and we are therefore using it in our current system. However, we have great reservations about the stability of the transformer. The balance between the two halves of the transformer secondary depends on the mechanical stability of the transformer core and on the long term stability of the winding inductance. These quantities are not controlled by the manufacturer in any documented way and a dependence of these quantities on ambient temperature is likely. We have minimized this effect by placing all of the electronics in the tiltmeter capsule. The temperature stability of the capsule is very high since it is quite deep. We have sealed the top of the hole as best we can to reduce the thermal conductivity of the air column down to the instrument.

Each channel of the system has been tested by replacing the sensor with two small adjustable capacitors. The capacitors are adjusted for a null, and the stability of this system is monitored. When such a test system is properly installed in a borehole it shows neither drift nor diurnal response at our usual recording sensitivity, and we are therefore reasonably confident that the electronics is acceptable for tidal work. However the long term aging of the transformer is still an unknown quantity, and it may eventually be a significant problem for long term high sensitivity (sub-microradian) measurements.

We have further reduced the sensitivity of the system to various spurious electrical signals by generating the power for the electronics at the bottom of the hole. We transmit raw d.c. down the hole (24 volts in our first designs, 12 volts currently) and this is converted to the plus and minus 15 volts required by the system by a commercial power inverter. The inverter is not sensitive to either the absolute magnitude of the supply voltage or to its ripple or r.f. content, and this eases the shielding problems. The signal outputs are also buffered by low impedance drivers and are transmitted differentially to the datalogger system at the top of the hole.

We have also isolated the signal ground from the capsule and from the cable shield to reduce pickup. The power is sent down the hole on a pair of leads isolated from the two other grounds (outer shield and signal return).

DATA ACQUISITION SYSTEM

The tiltmeter systems produce analog voltages proportional to tilt. The range of these voltages is between roughly plus and minus 12 volts. These voltages are received differentially by the datalogger so as not to introduce spurious noise due to ground loops between the capsule at the bottom of the hole and the recording system at the top. Each channel has an independently adjustable gain, offset, and frequency response (usually a low-pass filter).

Each datalogger can handle up to 16 analog channels. The analog channels are multiplexed to a single 12 bit analog-to-digital converter. A modem and a storage buffer complete the local part of the datalogger system.

The datalogger is controlled by the central computer (a PDP 11/34). Every 6 minutes, the central computer sends a series of control codes over a dedicated telephone link to the datalogger. These control codes cause the multiplexor to sequence through all of the active channels and report the digitzed voltage from each. The communication between the central computer and the site takes place at 300 baud using conventional frequency-shift-key type modems (equivalent to Bell System 103) and ordinary printing characters. (A complete scan of 16 channels requires about 8 seconds.) This makes it very easy to check the system since a conventional terminal may be inserted in place of either the computer or the datalogger to monitor system performance. The computer stores these values on a disk using conventional FORTRAN writes. The computer can control up to 15 different dataloggers, with a different set of up to 16 active channels each. The entire system is under the control of the real-time software supplied by the computer manufactuer (RSX 11 M) and has run for over a year with almost no problems.

Each datalogger can also respond to six distinct control codes and provide 6 distinct contact closures in response to receipt of the appropriate code. This is intended for remote control and re-zeroing, but we have not found this capability to be needed yet. However it will be necessary when the sites are more distant.

We have also begun the design of a datalogger system for use where a dedicated telephone link is too expensive or unavailable. Such a system must have some local storage and somewhat more independence than our current model since it must operate unattended for a day or two. Our plan is to link these sites to Boulder via dial-up telephone lines rather than dedicated lines, and to communicate with these more remote sites about once a day. This requires only a modest amount of storage and a rather simple control sequence. Our plan is to use dedicated micro-processors and small cartridge tape drives at these remote sites. These dedicated systems will be programmed in a simple language (e.g. BASIC) since neither the speed nor the complexity is very great.

SYSTEM SOFTWARE

In addition to the data acquisition program, we have also developed a large repertoire of analysis routines. We do not know, of course, exactly what sort of analysis we may wish to perform in the future, and our analysis routines are therefore small and modular. All of the routines read and write data in a standard, easily implemented format. Each data file contains a header block giving its start time, time interval, station coordinates, etc. Since all routines expect the same type of input file, the routines may be strung together in any way to produce arbitrarily complex analyses. Thus, for example, the output of the data acquisition task may be plotted on a CRT or on a hard copy device. The data may be digitally filtered, the filtered values may have their mean removed, then the Fourier spectrum may be computed and finally the spectrum may be plotted. The entire operation takes a few minutes, and the results of the operation are available immediately. If for some reason the analysis needs to be redone, it may be resumed from any intermediate point. The operator need not understand the internal workings of the programs, nor the format of the data files. The programs are extensively documented and all provide English-language diagnostics and a uniform command structure.

This software is very much the same as BOMM, a series of programs first developed at La Jolla about 20 years ago. In addition to more modern techniques, the current analysis package is more modular and it is therefore far easier to add a new routine to the system.

The greatest strength of the analysis package is that it has quite sophisticated on-line graphics so that the results of any operation may be graphically displayed. Additionally the information stored in the header block of each file makes it very easy both for the operators and the programs to keep track of data sets.

The programs are limited to a certain extent by the 16-bit length of the computer word. Neither programs nor data sets can be arbitrarily long without some special handling since a 16-bit word can only address 32768 words. A second, somewhat less serious limitation comes from the rather limited exponent range of the floating point system (exponents are limited to the range -38 to +38), and this limitation may become significant when dealing with the intermediate results of lengthy calculations.

FIELD TESTS

We have conducted field tests of various sensor configurations at a site on the Department of Commerce campus in Boulder. The site is not near the main buildings and is therefore reasonably quiet. We have conducted tests using holes of 4 different depths (20 feet, 50 feet, 100 feet and 200 feet depth). Most of our tests have been aimed at evaluating different electronics designs and different sensors, but we have also studied the behaviour of identical systems in holes of different depth. We are reasonably certain that a 20 foot hole is too shallow, since measurements made at 20 foot depth are too much influenced by surface perturbations. At the other extreme, the difficulties of installing and aligning an instrument in the 200 foot hole seem to outweigh the advantage of operating at that depth. We have therefore done most of our work at a depth of either 50 feet or 100 feet, and we have decided to use a depth of 100 feet in all future installations.

We have studied many different electronic configurations. We have slowly been driven to put more and more of the electronics at the bottom of the hole with the sensor since almost all of the parts show unacceptably large thermal sensitivity when placed at the top. Our current system has all of the electronics at the bottom of the hole including the power converter.

One of our longest records to date, obtained with an instrument at a depth of 50 feet, is shown in fig. 3. The earth tides are clearly visible and the drift is quite small. The large low frequency term is probably produced by the large change in temperature and water table level that accompanies the coming of spring.

FUTURE PLANS

We have started to prepare at second site at Erie, Colorado, about 25 miles East of Boulder. This site is flat and should be very quiet. We have also begun discussions about acquiring sites in Wyoming near Yellowstone National Park.

We are still looking at various sensor/electronics combinations.

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FIGURE CAPTIONS

Fig. 1. Schematic of the boreholes used in the current work.

Fig. 2. Side view of the sensor assembly showing the method used to level the sensors.

Fig. 3. A tilt record obtained from a sensor in a 50-foot borehole. Each minor division on the Y-axis corresponds to a tilt of 0.14 microradian. Each minor division on the X-axis corresponds to a time of approximately 6 days.

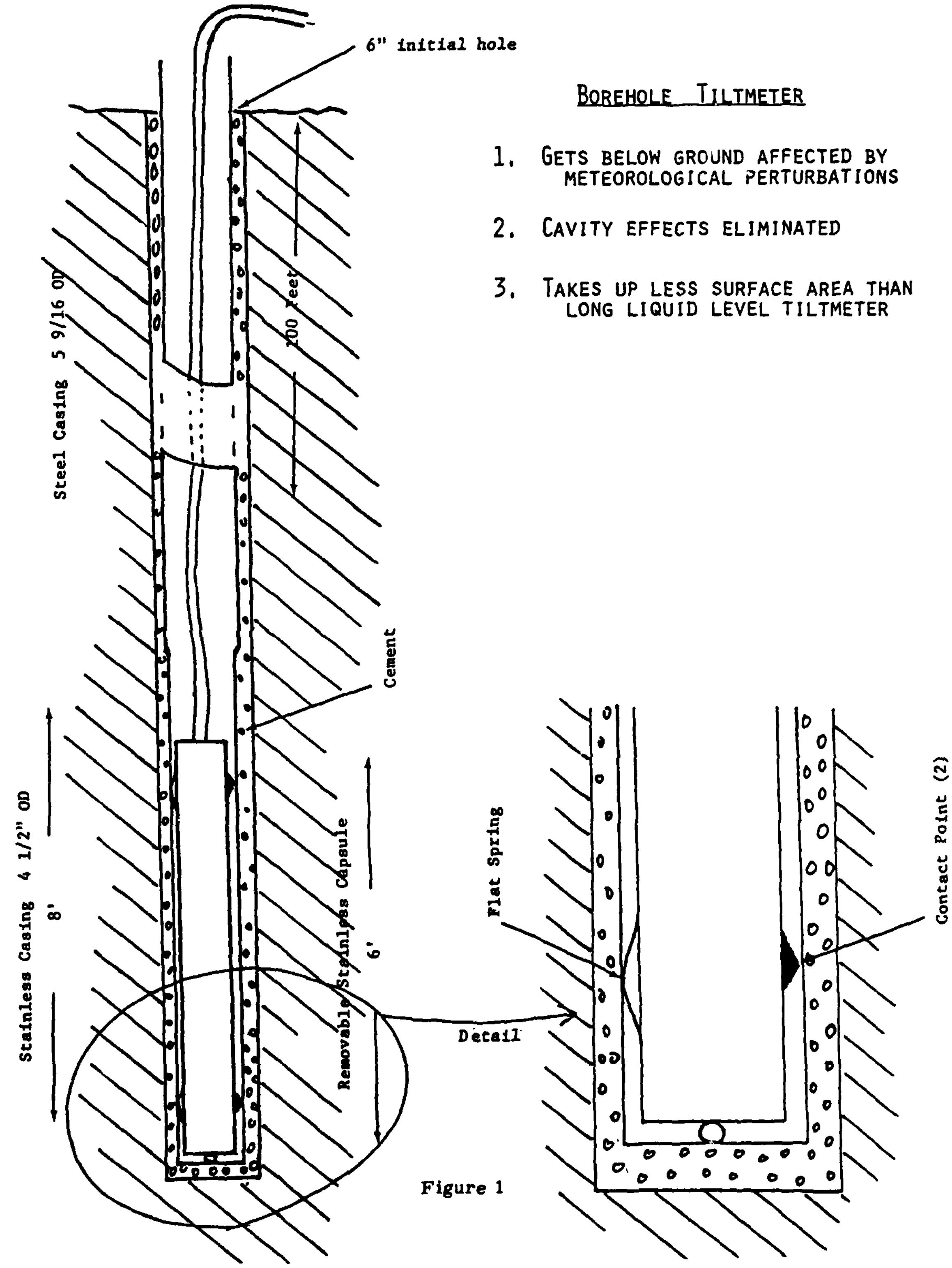

Figure 1

Borehole Tiltmeter

1. Gets below ground affected by meteorological perturbations
2. Cavity effects eliminated
3. Takes up less surface area than long liquid level tiltmeter

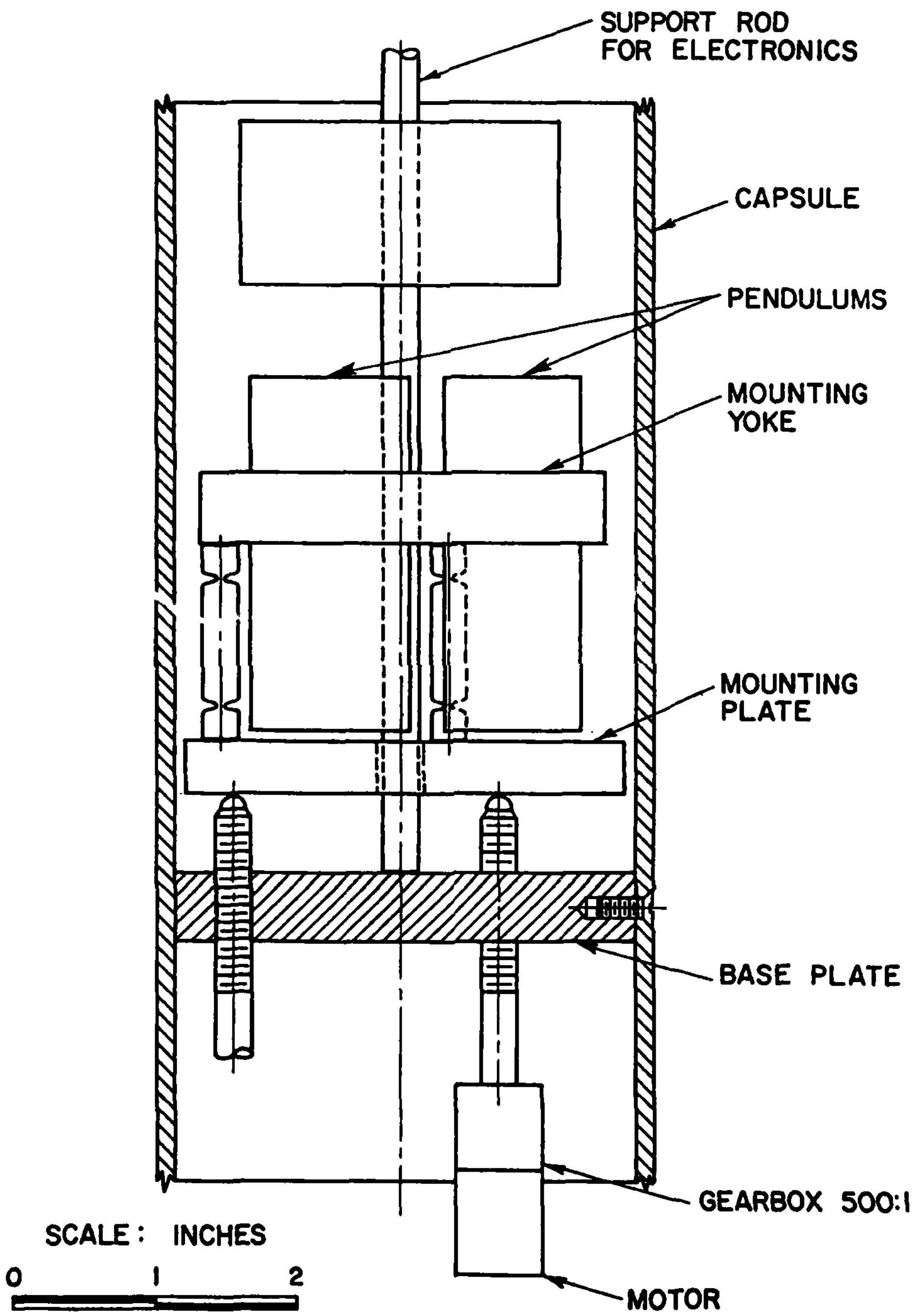
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Figure 2

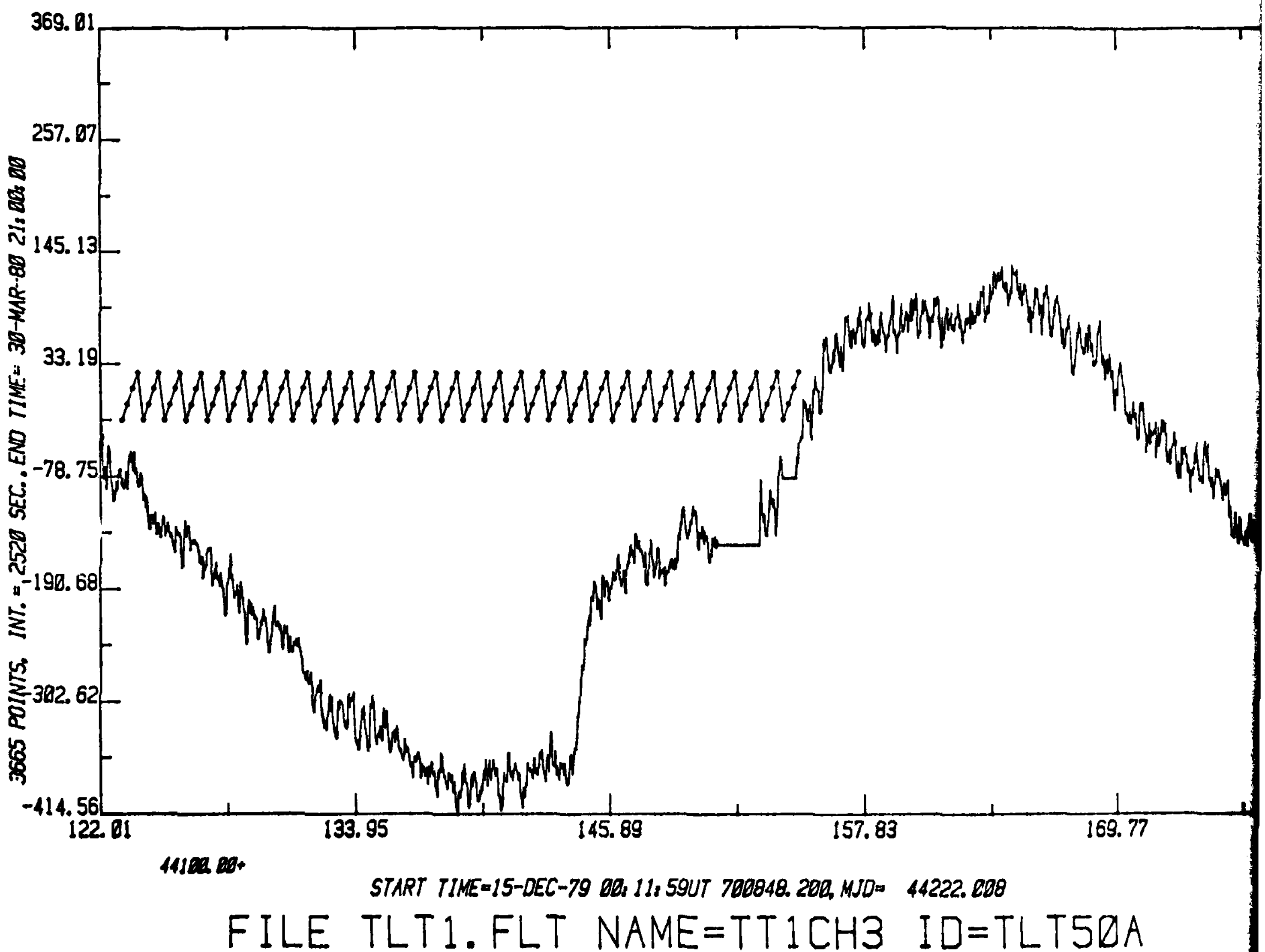

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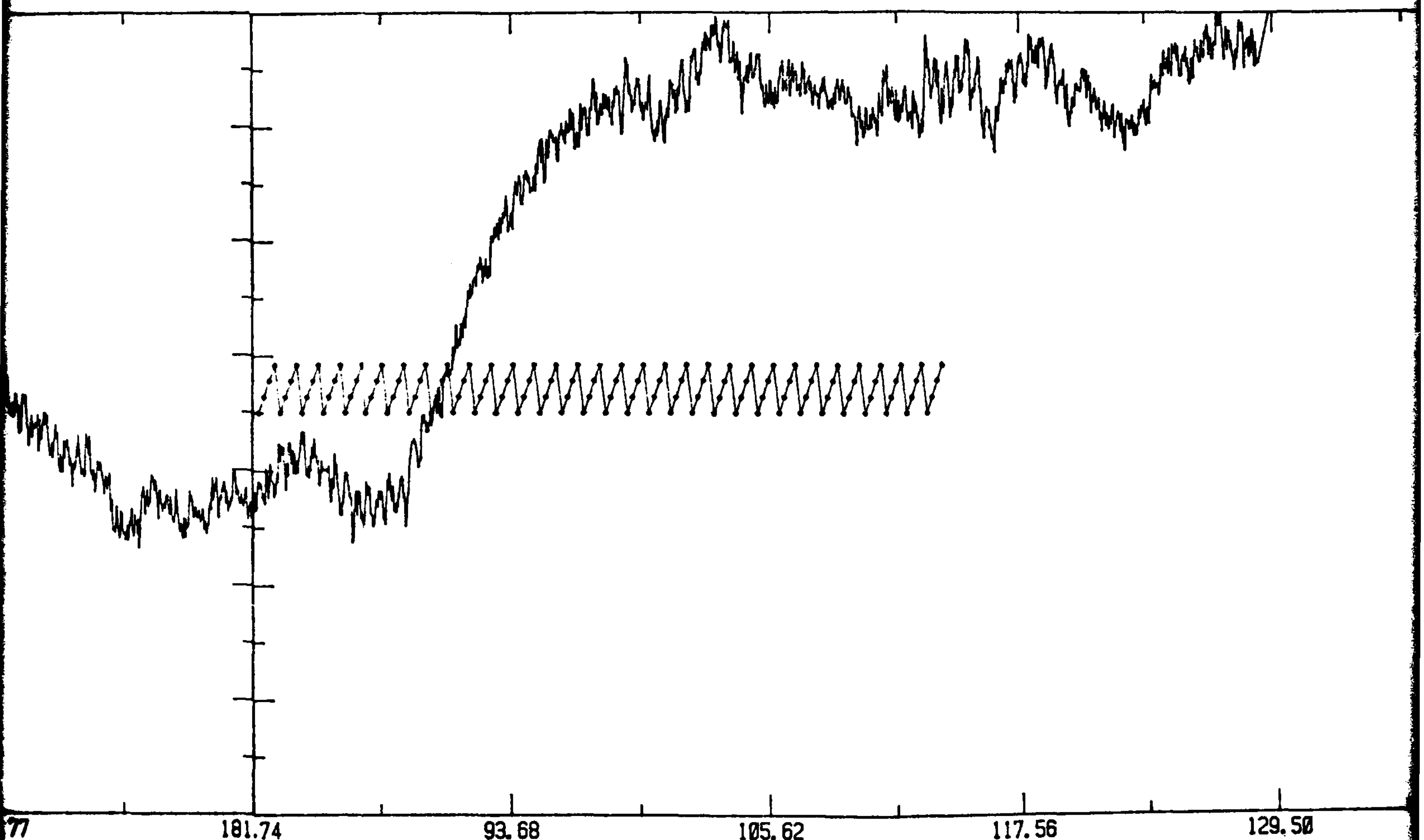
Figure 3



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